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# TECHNICAL NOTE

## D-455

EFFECT OF REYNOLDS NUMBER ON THE FORCE AND PRESSURE  
DISTRIBUTION CHARACTERISTICS OF A TWO-DIMENSIONAL  
LIFTING CIRCULAR CYLINDER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
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## SUMMARY

A two-dimensional lifting circular cylinder has been tested over a Mach number range from 0.011 to 0.32 and a Reynolds number range from 135,000 to 1,580,000 to determine the force and pressure distribution characteristics. Two flaps having chords of 0.37 and 6 percent of the cylinder diameter, respectively, and attached normal to the surface were used to generate lift. A third configuration which had 6-percent flaps 180° apart was also investigated. All flaps were tested through a range of angular positions. The investigation also included tests of a plain cylinder without flaps.

The lift coefficient showed a wide variation with Reynolds number for the 6-percent flap mounted on the bottom surface at the 50-percent-diameter station, varying from a low of about 0.2 at a Reynolds number of 165,000 to a high of 1.54 at a Reynolds number of 350,000 and then decreasing almost linearly to a value of 1.0 at a Reynolds number of 1,580,000. The pressure distribution showed that the loss of lift with Reynolds number above the critical was the result of the separation point moving forward on the upper surface. Pressure distributions on a plain cylinder also showed similar trends with respect to the separation point.

The variation of drag coefficient with Reynolds number was in direct contrast to the lift coefficient with the minimum drag coefficient of 0.6 occurring at a Reynolds number of 360,000. At this point the lift-drag ratios were a maximum at a value of 2.54.

Tests of a flap with a chord of 0.0037 diameter gave a lift coefficient of 0.85 at a Reynolds number of 520,000 with the same lift-drag ratio as the larger flap but the position of the flap for maximum lift was considerably farther forward than on the larger flap. Tests of two 6-percent flaps spaced 180° apart showed a change in the sign of the lift developed for angular positions of the flap greater than 132° at subcritical Reynolds numbers. These results may find use in application to aircraft using forebody strakes. The drag coefficient developed by the flaps when normal to the relative airstream was approximately equal to that developed by a flat plate in a similar attitude.

## INTRODUCTION

At the present time investigations are being made by various agencies to provide information on possible methods of recovering rocket boosters. One such investigation by the National Aeronautics and Space Administration is concerned with the generation of lift on a body of revolution moving with its axis normal to the flight direction. In this method the lift is generated over the length of a body by the deflection of a small flap on the bottom surface. A recent investigation (ref. 1) on a circular cylinder of fineness ratio 10 has shown that relatively high lift coefficients can be obtained in this manner. The data of reference 1 show very large losses of lift coefficient for Mach numbers above 0.3. It is possible that the loss of lift at the higher Mach numbers may in part be a Reynolds number effect since Mach number and Reynolds number were not independently varied during the test. It was shown in reference 1 that the drag of a plain cylinder increased with Reynolds number above the critical for low subsonic Mach numbers; therefore, it is reasonable to assume that the lift coefficient may also be affected by Reynolds number. The purpose of this investigation was therefore to determine the effect of Reynolds number on the lifting characteristics of a circular cylinder in the Mach number range where compressibility effects are small.

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The investigation was made on a two-dimensional circular cylinder over a range of Reynolds numbers from 135,000 to 1,580,000 based on cylinder diameter. The lift and drag forces on the cylinder were measured and, in addition, pressure distributions were obtained as an aid in understanding Reynolds number effects. Data were obtained on two different sizes of flaps located on the lower surface at the 50-percent streamwise position; other flap locations were also studied. For comparative purposes data were also obtained on a plain cylinder (without flaps). In addition to these tests, tests were also made of a configuration which had flaps 180° apart. These data may have application to airplane configurations using forebody strakes.

## SYMBOLS

The data are presented with respect to the wind axes as indicated in figure 1.

c flap chord

$c_d$  section drag coefficient,  $\frac{\text{Drag per unit length}}{\frac{\rho V^2}{2}}$

$c_l$	section lift coefficient, $\frac{\text{Lift per unit length}}{d \frac{\rho}{2} V^2}$
$c_m$	section pitching-moment coefficient about cylinder axes, $\frac{\text{Pitching moment per unit length}}{d^2 \frac{\rho}{2} V^2}$
$c_p$	pressure coefficient, $\frac{p_l - p}{\frac{\rho}{2} V^2}$
$d$	cylinder diameter
$M$	Mach number
$p$	free-stream static pressure
$p_l$	local static pressure on cylinder
$R$	Reynolds number
$V$	free-stream air velocity
$\rho$	free-stream air density
$\delta$	flap angular position relative to wind, positive from trailing edge down, deg
$\theta$	radial angle relative to wind, measured from leading edge (either upper or lower surface), deg
Subscript:	
max	maximum

#### MODELS AND EQUIPMENT

The cylinder used in the investigation had a diameter of 8.34 inches and completely spanned the test section of the Langley 300-MPH 7- by 10-foot tunnel as shown in the diagram of figure 1. The cylinder was constructed of mahogany and lacquered to produce a smooth finish. In order to minimize any effects which might be caused by air leakage through the small clearance gaps where the cylinder passed through the floor and

ceiling, the cylinder was equipped with end plates to prevent spanwise flow. The standard mechanical balance system of the tunnel was used to measure the lift and drag.

The flaps used in the investigation are illustrated in figure 1. The smallest flap was made of a strip of metal 1/32 inch by 1/8 inch and when attached to the bottom surface had a chord of 0.0037 cylinder diameter. The larger flap which was made of 1/2-inch by 1/2-inch angle had a chord of 0.06 diameter. (These flaps hereafter will be referred to as the 0.37-percent and 6-percent flap, respectively.) The side of the angle used for attaching the larger flap was placed in the downstream direction. A third flap configuration was made up of two 1/2-inch by 1/2-inch angles attached 180° apart. All flaps were attached by counter-sunk wood screws.

One set of pressure orifices was installed near the midspan with tubes spaced approximately 15° apart around the surface. The pressures were recorded on film from an alcohol manometer board.

#### TEST CONDITIONS

For most of the tests in the investigation the dynamic pressure was held constant and the flap position  $\delta$  was varied by rotating the cylinder through an angular range. For the remainder of the test the flap was held fixed at  $\delta = 90^\circ$  (see fig. 1) while the dynamic pressure was varied. This variation of dynamic pressure corresponded to a range of Reynolds numbers from 135,000 to 1,580,000, based on the cylinder diameter of 0.695 foot. The flow turbulence factor was 1. All tests were made at Mach numbers well below the critical Mach number for the cylinder. The approximate variation of Reynolds number with Mach number for these tests is shown in figure 2.

#### RESULTS AND DISCUSSION

The lift and drag characteristics of the various flap configurations studied in this investigation are presented in figures 3 to 7. Pressure distributions which correspond to some of the data points of figures 3 to 7 are presented in figures 8 to 13. Pitching-moment data are not presented. An approximation to the pitching-moment coefficient can be obtained from the equation

$$c_m = \frac{1}{2} \Delta c_p \frac{c}{d}$$

where  $\Delta c_p$  is the pressure-coefficient difference between the upstream and downstream side of the flap.

### Lifting Flaps

Effect of Reynolds number.- The effect of Reynolds number on the aerodynamic characteristics of the cylinder with the 6-percent flap ( $\delta = 90^\circ$ ) is shown in figure 3. The lift coefficient shows a large variation with Reynolds number over the complete range tested. At the subcritical Reynolds number of 165,000, a  $c_l$  of approximately 0.2 was obtained while just above the transition range ( $R = 350,000$ ) a maximum  $c_l$  of 1.54 was obtained. As the Reynolds number was further increased, the lift coefficient decreased almost linearly to a value of  $c_l = 1.0$  at  $R = 1,580,000$ , the limit of the tests.

The lift data of figure 3 are replotted in figure 4 along with some selected pressure diagrams for both the plain cylinder (nonlifting) and the lifting cylinder to indicate the type of pressure distributions associated with the lift generation. The plain-cylinder pressure distribution for a Reynolds number of 190,000 was obtained from reference 2. It is apparent from the pressure diagrams of figures 4 and 8 that the presence of the 6-percent flap ( $\delta = 90^\circ$ ) causes an appreciable alteration of the pressure distribution. On the lower surface the negative pressure loop of the basic cylinder is almost completely destroyed. On the upper surface the pressure coefficients show a material gain over that of the basic cylinder as a result of the circulation established by the flap. In addition to the effects noted on the upper and lower surface, the circulation also produced a considerable increase in the negative pressure coefficients over the rear of the cylinder which results in a considerable increase in drag coefficient. (See fig. 3.)

A further study of figures 4 and 8 shows the cause of the decrease in lift coefficient with increase in Reynolds number mentioned previously. These data show that, as the Reynolds number is increased above 426,000, the separation point in general moves forward on the upper surface (about  $40^\circ$  in the range of Reynolds numbers from 426,000 to 1,308,000). This forward movement of the separation point reduces the area affected by the high negative pressures. Also noted in this range of Reynolds numbers is a decrease in the peak negative pressure coefficient ahead of the separation point.

The forward movement of the separation point and the reduction of the peak pressure coefficient with increased Reynolds number may also be observed in the plain cylinder data of figures 4 and 9 for Reynolds numbers greater than 950,000. The reduction of peak pressures on the

The negative lift shown in figure 7 for the subcritical Reynolds number (190,000) for values of  $\delta > 130^\circ$  appears to be associated with laminar separation on the top surface and a turbulent reattachment on the bottom surface. On the top surface the typical subcritical Reynolds number pressure distribution is indicated in figure 13(a) with separation over more than half of the upper surface. On the lower surface the pressure shows a pattern similar to that for the supercritical Reynolds number in that the negative pressure coefficient increases behind the flap. Evidently, the turbulent flow from the flap reattaches to the cylinder and the turbulent boundary layer allows the lower surface separation point to occur farther back on the cylinder. The asymmetry of the resulting flow produces the negative lift force.

The two flaps  $180^\circ$  apart (see fig. 7) may also be considered as a drag-producing device in which case the cylinder fitted with flaps ( $c/d = 0.06$ ) has nearly as high a maximum drag coefficient at a Reynolds number of 520,000 as a flat plate normal to the airstream. At  $\delta = 90^\circ$  the flaps with separated flow behind gave a drag coefficient of 1.8 which is close to the value of 1.98 quoted in reference 5 for a two-dimensional flat plate. The value of  $c_d = 1.8$  represents a sixfold increase in the drag coefficient when compared with that of the plain cylinder at a Reynolds number of 520,000. (See fig. 3.)

#### SUMMARY OF RESULTS

A low-speed investigation has been made on a two-dimensional lifting circular cylinder over a Reynolds number range from 135,000 to 1,580,000 to determine the force and pressure distribution characteristics. The results are summarized as follows:

1. The critical Reynolds number for the lifting cylinder with a 6-percent flap deflected  $90^\circ$  was approximately 350,000.

2. The lift coefficient which showed a wide variation with Reynolds number varied from a low of about 0.2 at a Reynolds number of 165,000 to a high of 1.54 at a Reynolds number of 350,000 and then decreased almost linearly to a value of 1.0 at a Reynolds number of 1,580,000 for the 6-percent flap deflected  $90^\circ$ .

3. The drag coefficient of the 6-percent flap configuration varied linearly from a minimum of 0.6 at a Reynolds number of 350,000 to a maximum of 0.9 at a Reynolds number of 1,580,000.

4. The lift-drag ratio for a 6-percent flap deflected  $90^\circ$  varied from a low of 0.15 at subcritical Reynolds numbers to a maximum of 2.54 at the



beginning of the supercritical range. It then decreased with increasing Reynolds number.

5. The pressure distributions for the 6-percent flap configuration showed that the loss of lift with Reynolds number was the result of the separation point moving forward on the upper surface. Pressure distributions over a plain cylinder also showed similar trends with respect to the separation point.

6. Tests of a 0.37-percent flap gave a lift coefficient of 0.85 at a Reynolds number of 520,000 with the same lift-drag ratio as the larger flap but the position of the flap for maximum lift was considerably farther forward than on the larger flap.

7. Tests of two 6-percent flaps spaced  $180^\circ$  apart showed a change in the sign of the lift developed for positions of the flap greater than  $132^\circ$  at subcritical Reynolds number. The drag coefficient developed by the flaps when normal to the relative airstream was approximately equal to that developed by a flat plate in a similar attitude.

Langley Research Center,  
National Aeronautics and Space Administration,  
Langley Field, Va., June 1, 1960.

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1. Lockwood, Vernard E., and McKinney, Linwood W.: Lift and Drag Characteristics at Subsonic Speeds and at a Mach Number of 1.9 of a Lifting Circular Cylinder With a Fineness Ratio of 10. NASA TN D-170, 1959.
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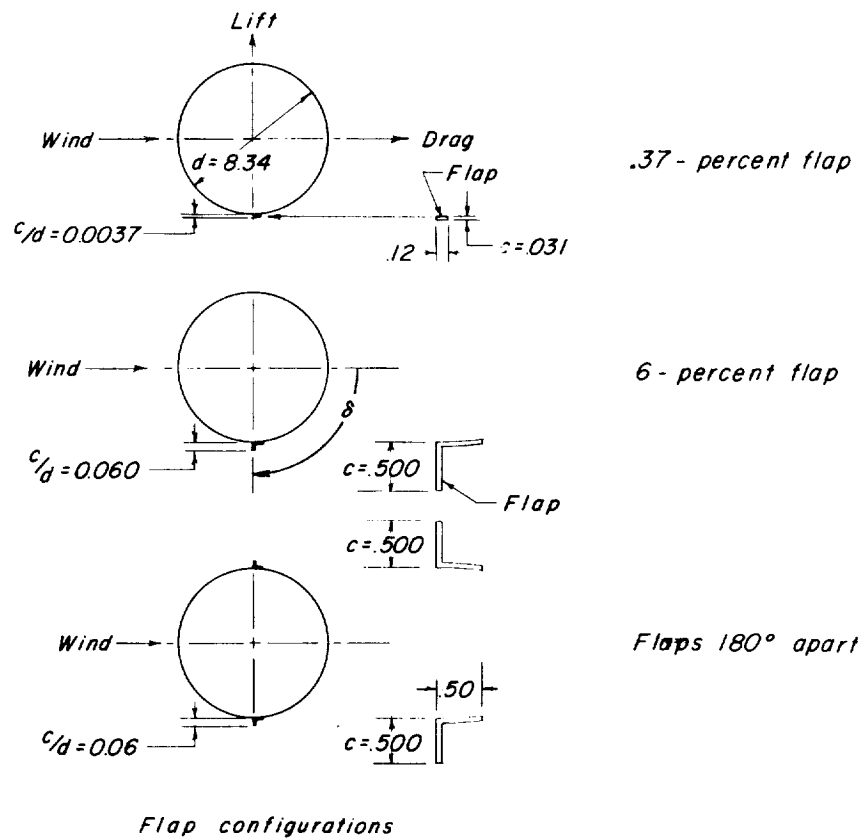
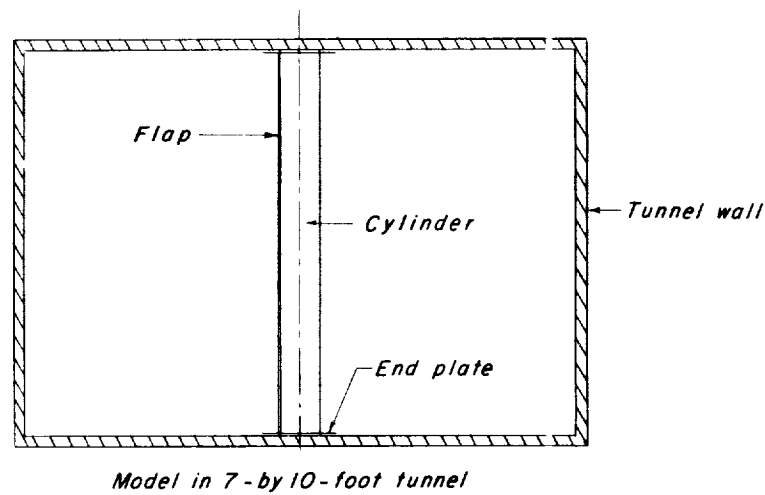


Figure 1.- Diagram of model and flaps used in the investigation. (All dimensions are in inches.)

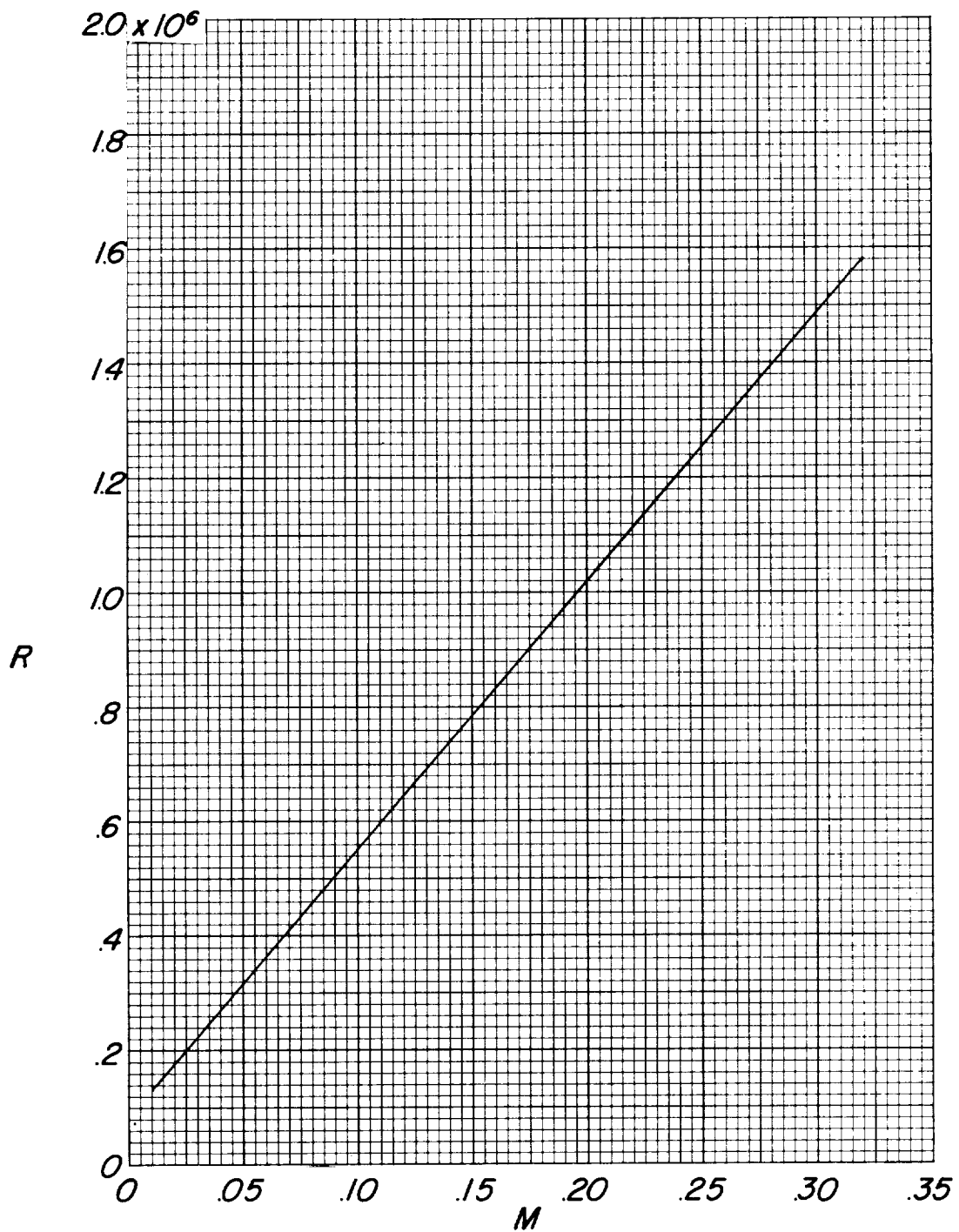


Figure 2.- Variation of Reynolds number with Mach number for the investigation.

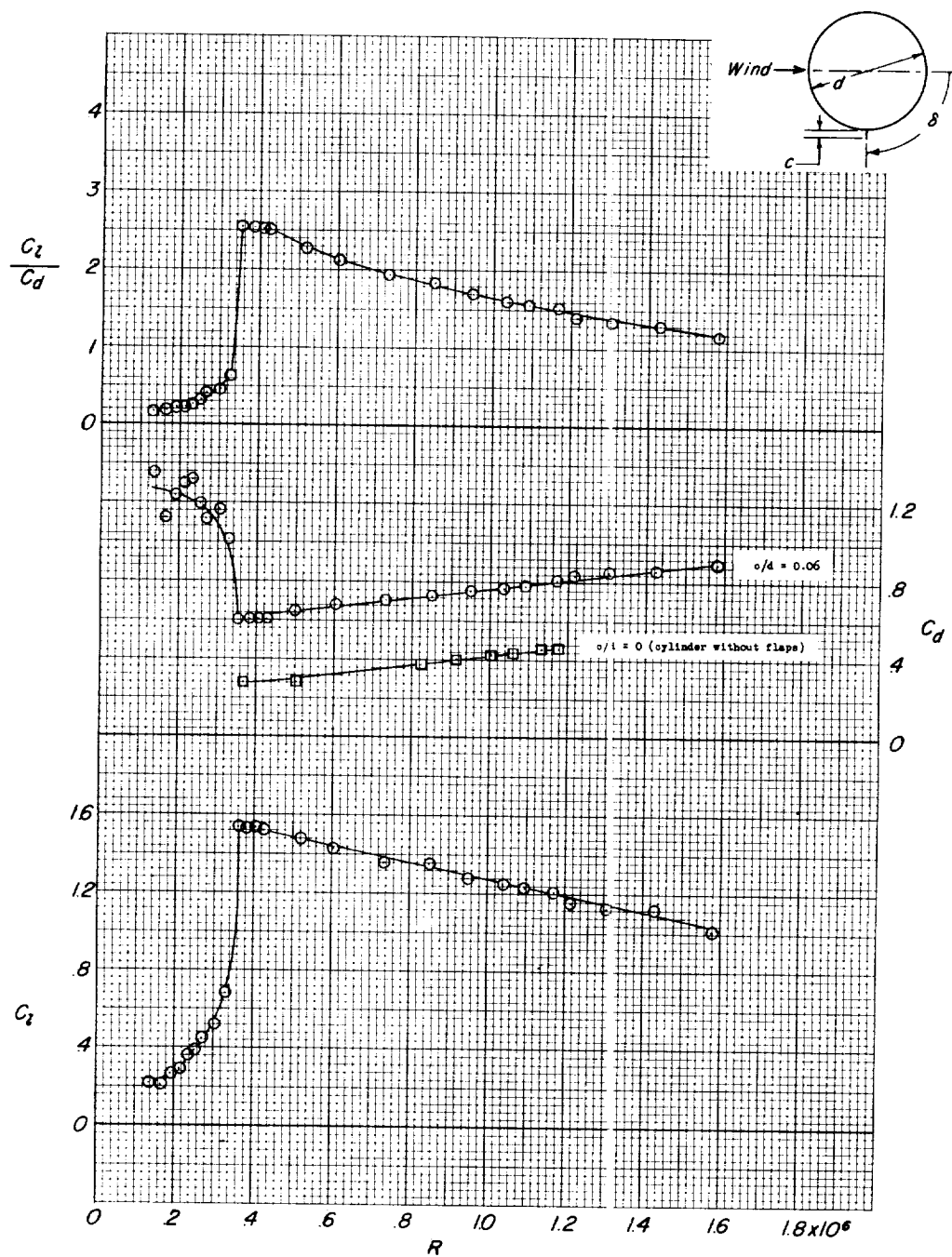


Figure 3.- Effect of Reynolds number on the aerodynamic characteristics of a lifting cylinder. (Plain cylinder data included.)  $c/d = 0.06$ ;  $\delta = 90^\circ$ .

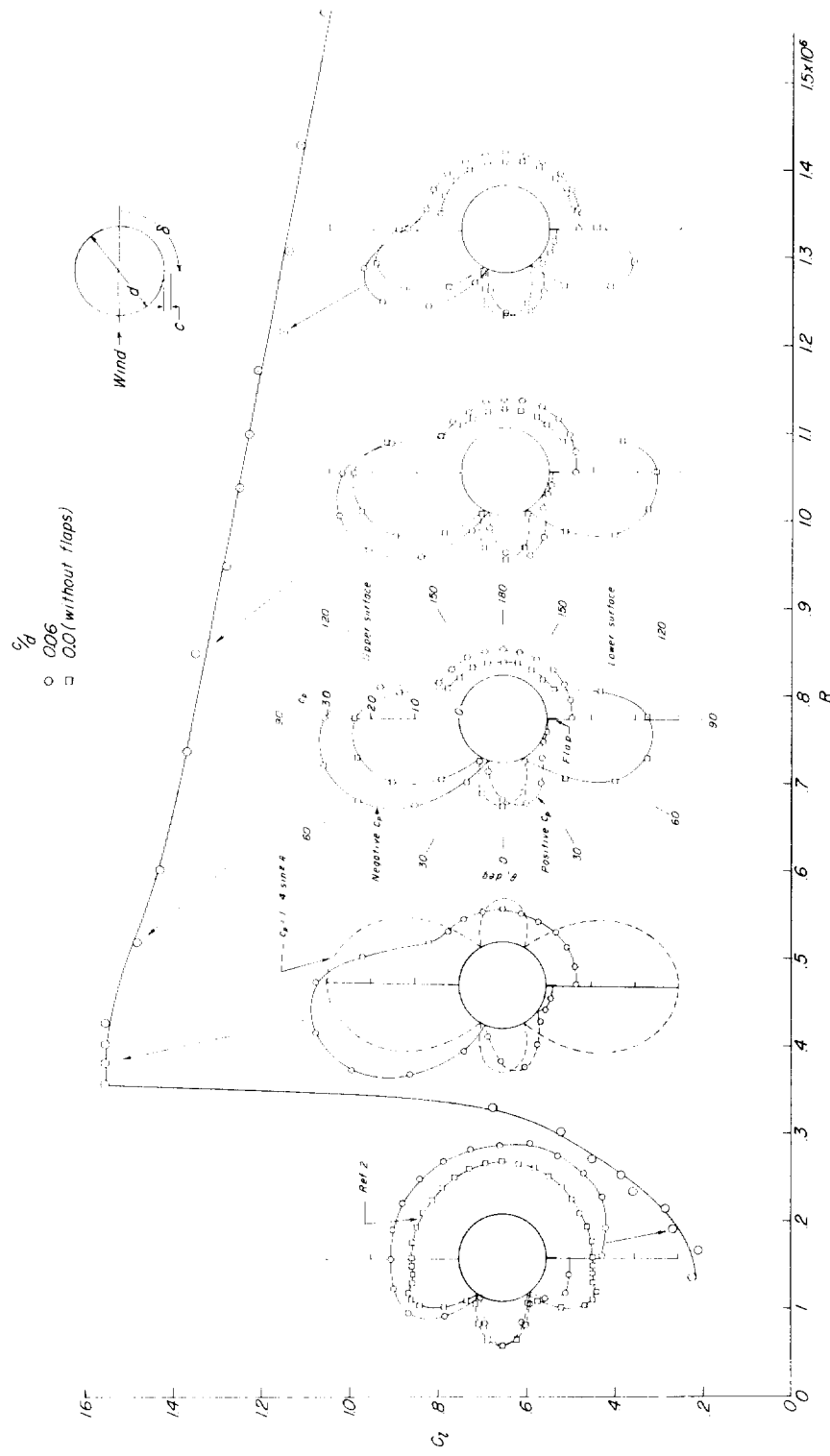


Figure 4.- Effect of Reynolds number on the lift and pressure distribution characteristics of a lifting cylinder.  $\delta = 90^\circ$ .

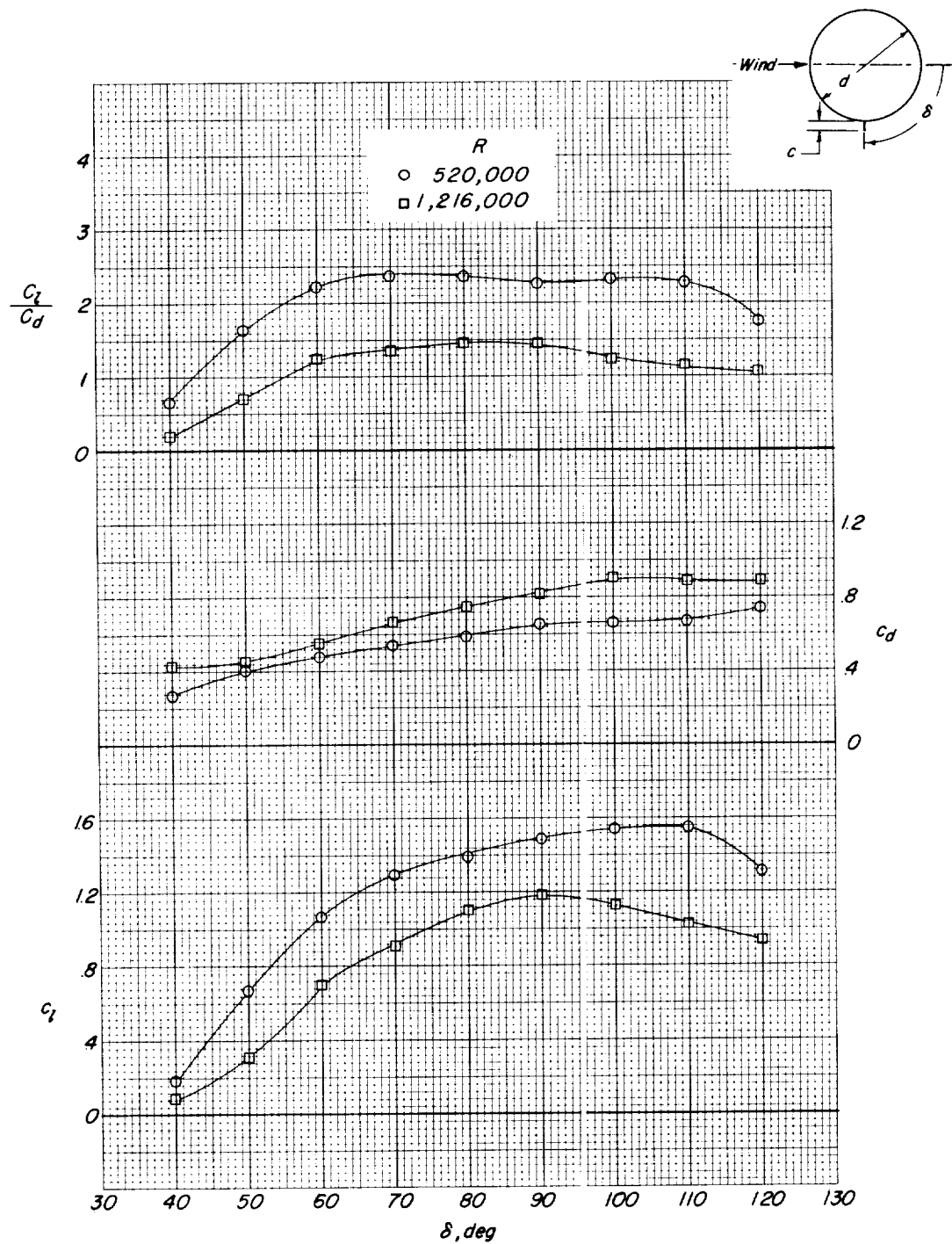


Figure 5.- Effect of flap angular position on the aerodynamic characteristics of a lifting cylinder for two Reynolds numbers.  $c/d = 0.06$ .

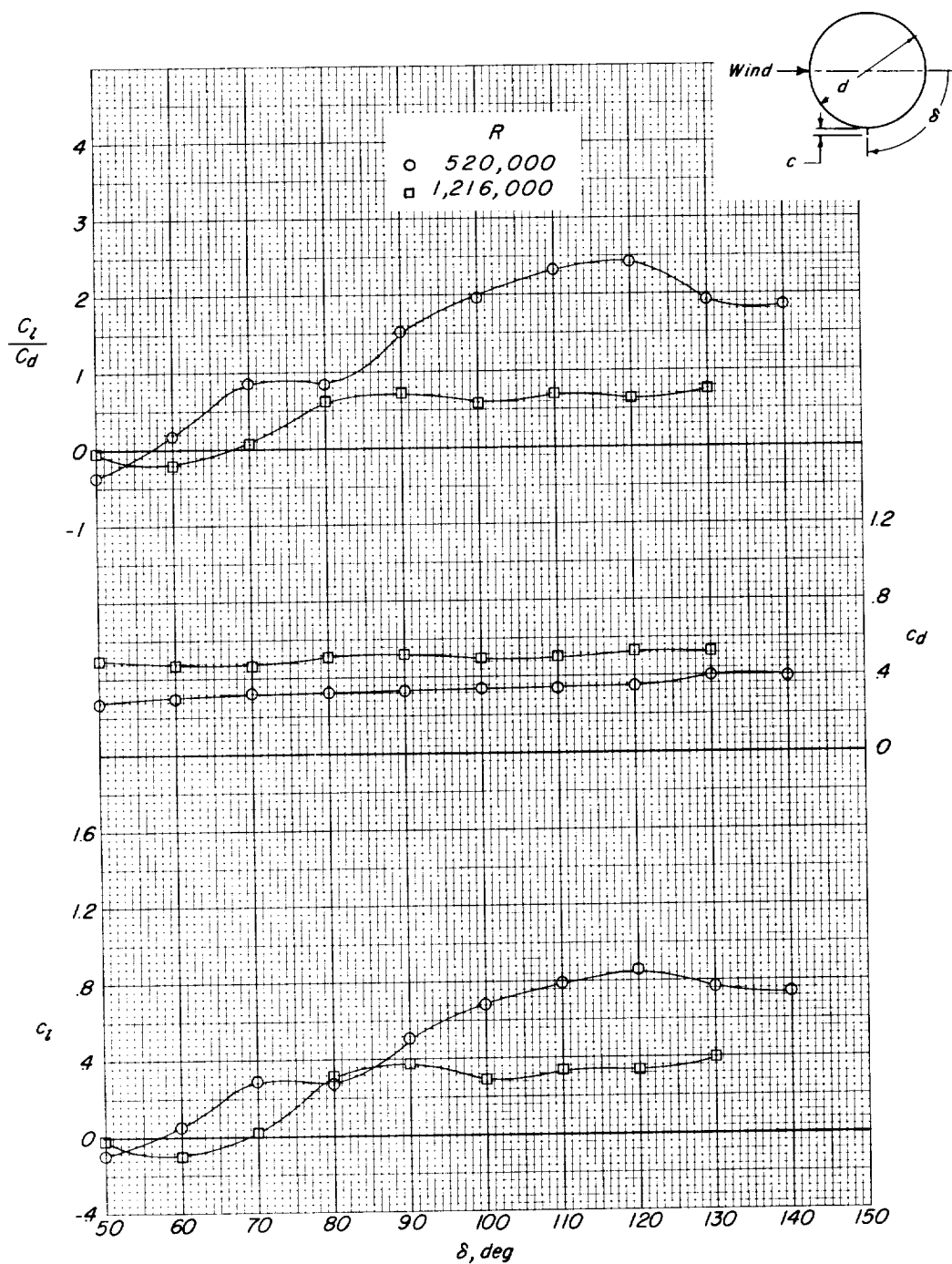


Figure 6.- Effect of flap angular position on the aerodynamic characteristics of a lifting cylinder for two Reynolds numbers.  $c/d = 0.0037$ .

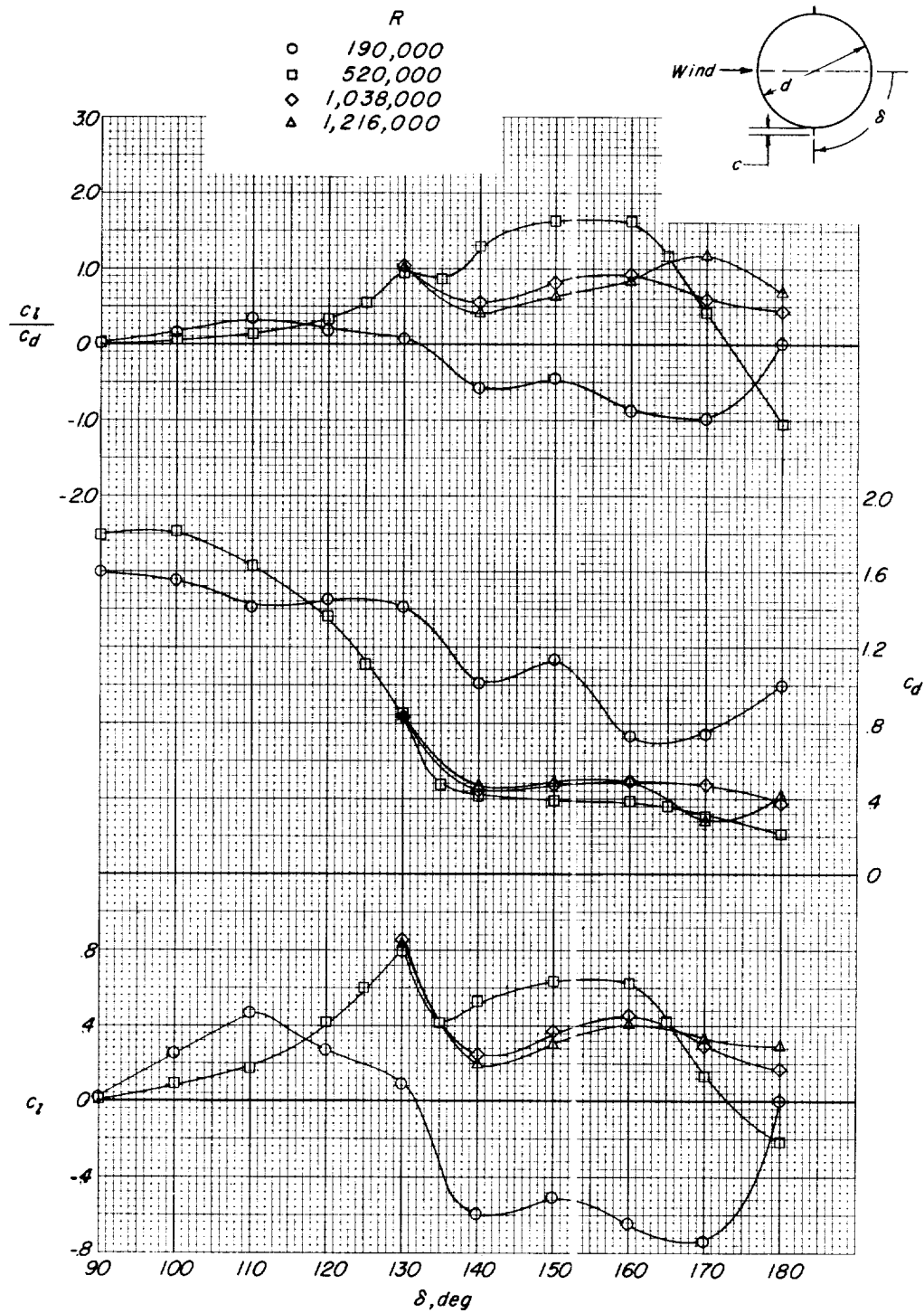


Figure 7.- Effect of flap angular position on the aerodynamic characteristics of a cylinder having two flaps  $180^\circ$  apart.  $c/d = 0.06$ .



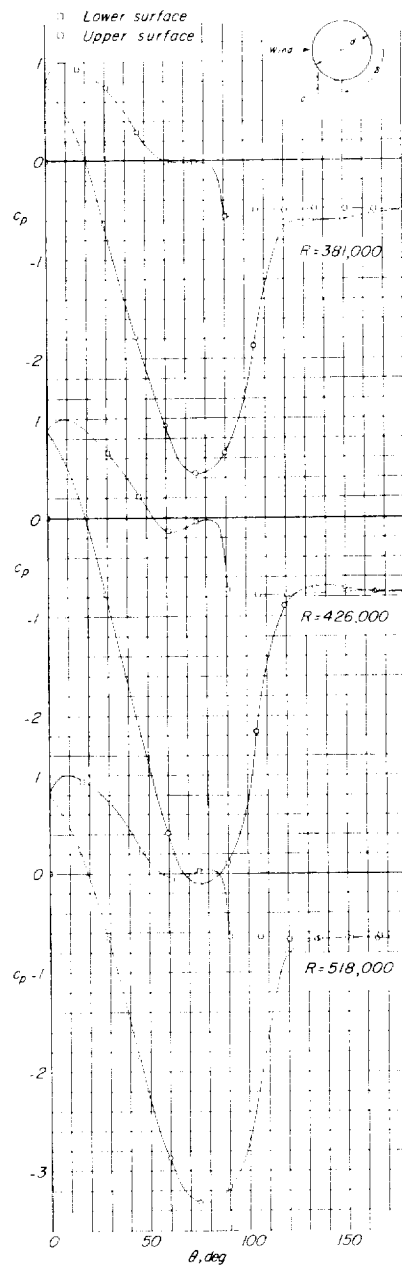


Figure 8.- Effect of Reynolds number on the pressure distribution about a lifting cylinder.  $c/d = 0.06$ ;  $\delta = 90^\circ$ .

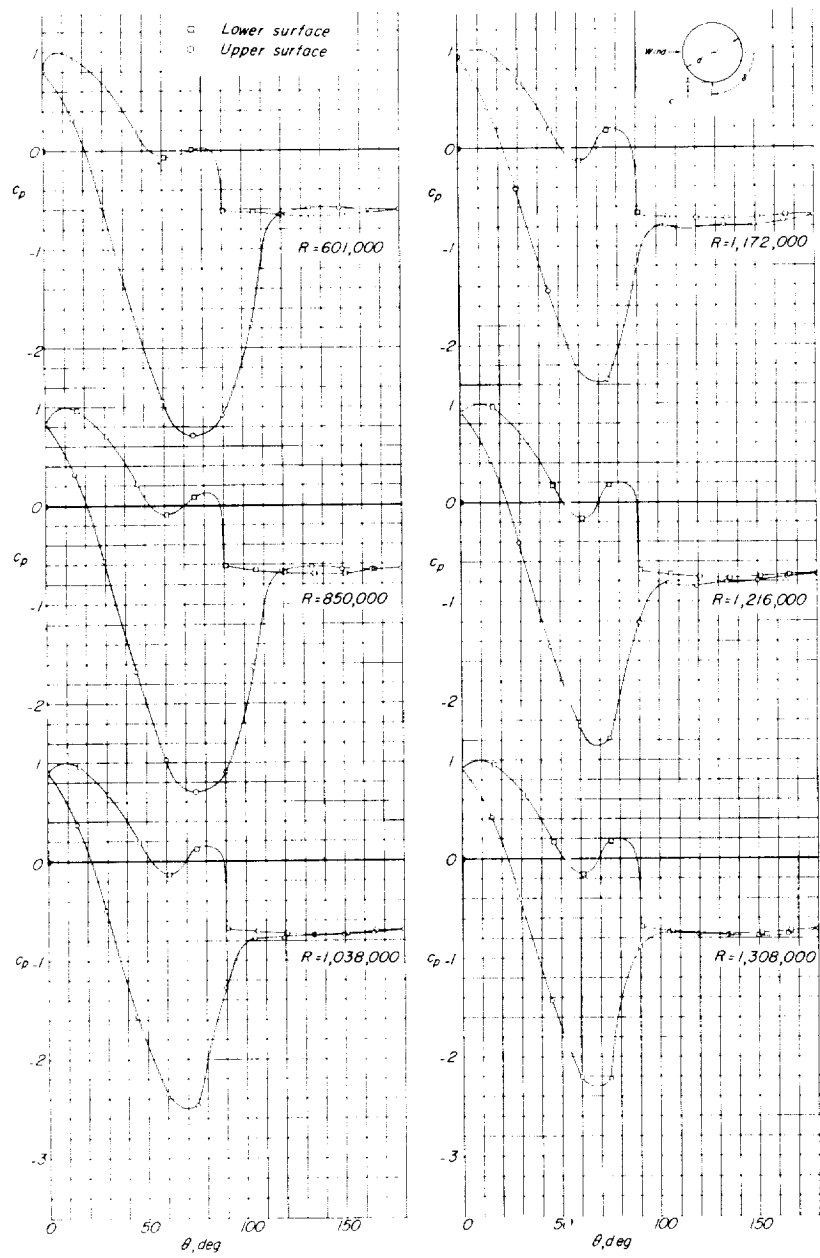


Figure 8.- Concluded.

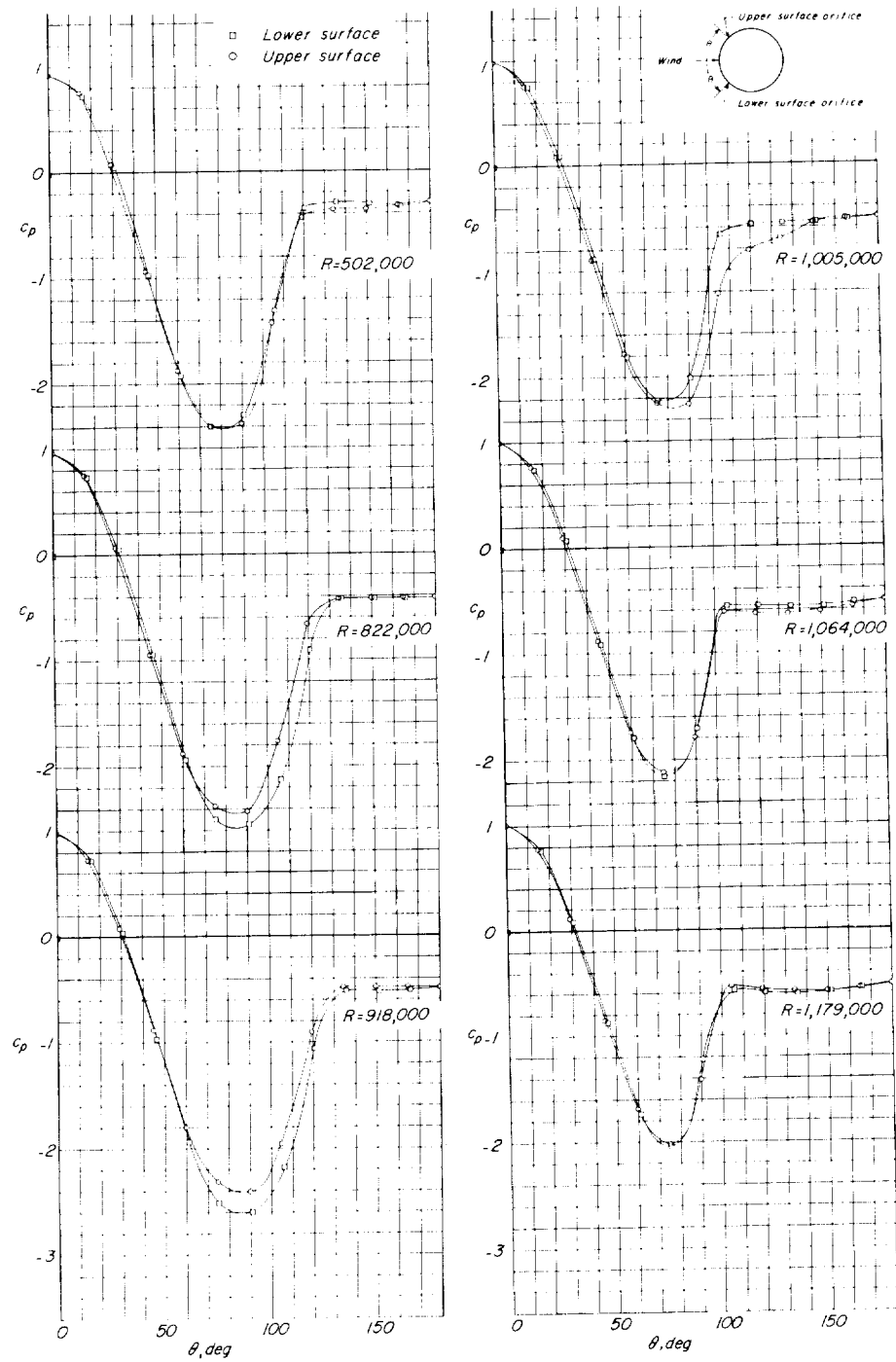


Figure 9.- Effect of Reynolds number on the pressure distribution about a plain cylinder.

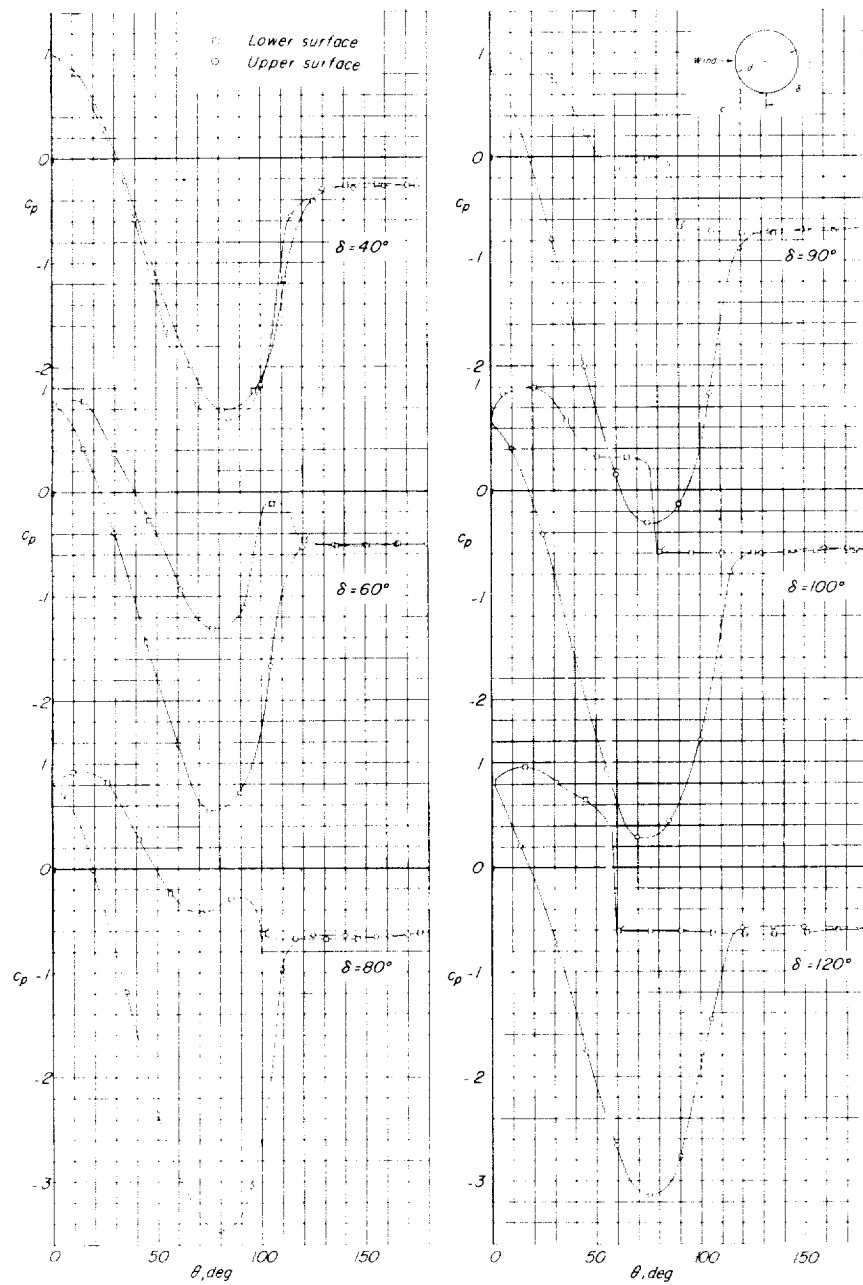
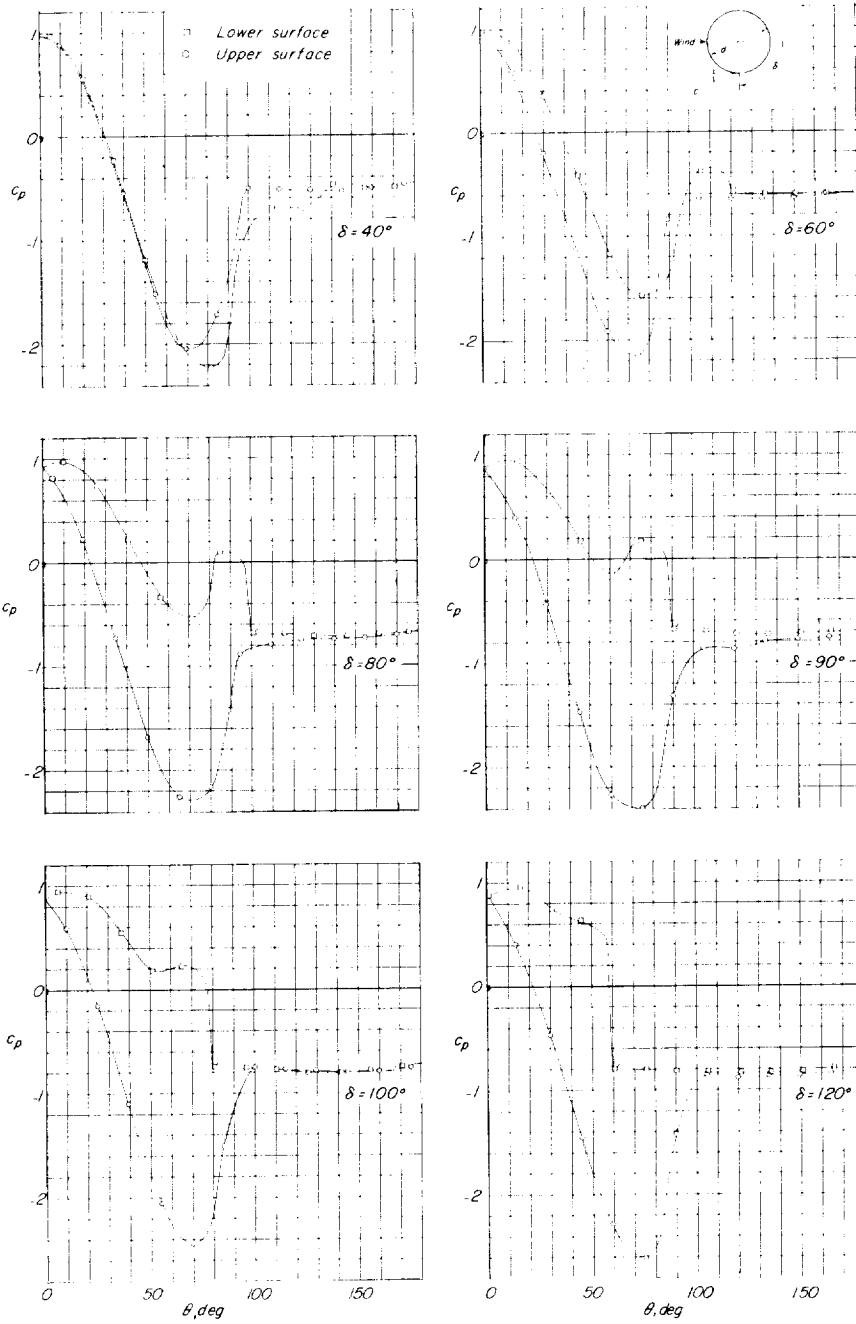
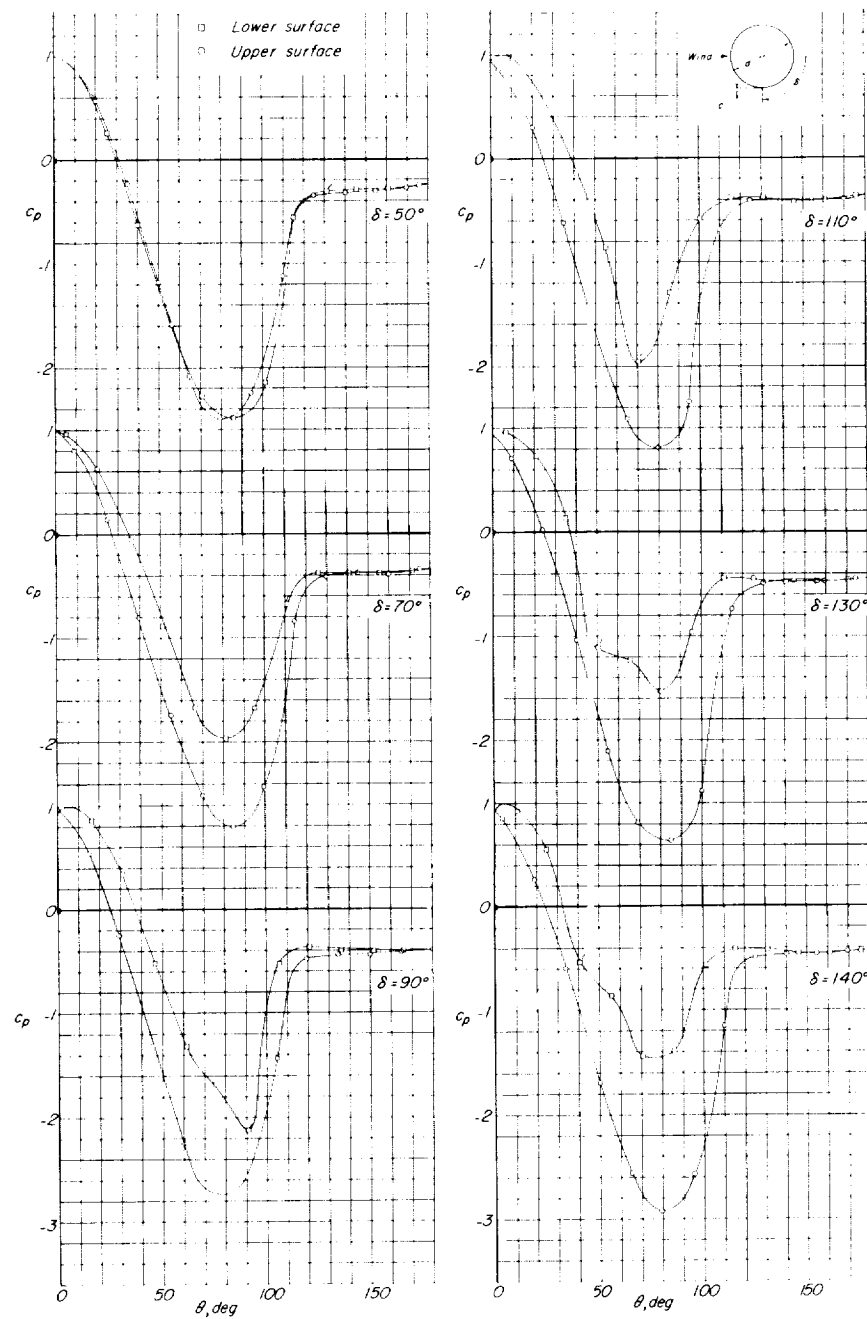
(a)  $R = 520,000$ .

Figure 10.- Effect of flap angular position on the pressure distribution about a lifting cylinder. Tick refers to flap position.  $c/d = 0.06$ .



(b)  $R = 1,216,000$ .

Figure 10.- Concluded.



(a)  $R = 520,000$ .

Figure 11.- Effect of flap angular position on the pressure distribution about a lifting cylinder. Ticks indicate flap position.  $c/d = 0.0037$ .

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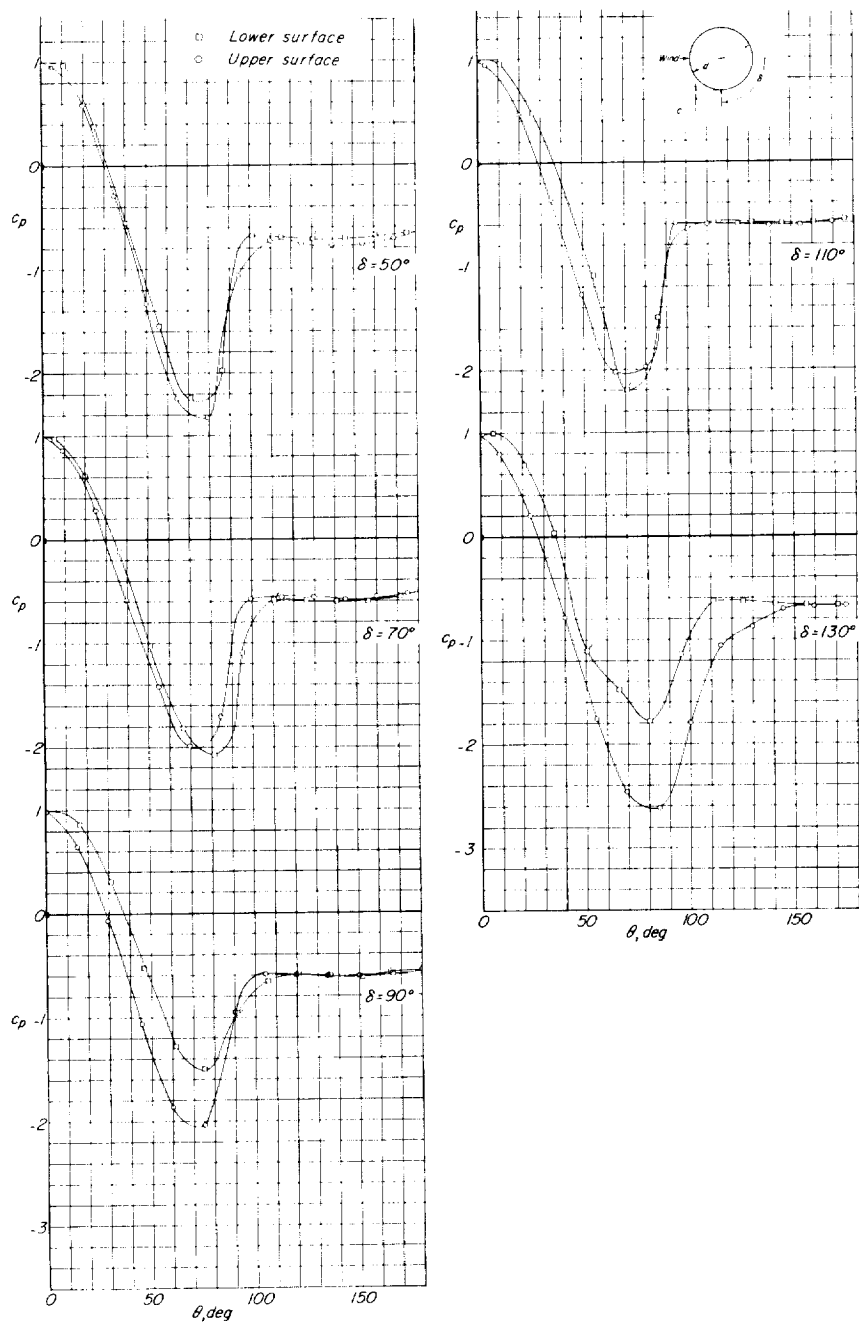
(b)  $R = 1,216,000$ .

Figure 11.- Concluded.

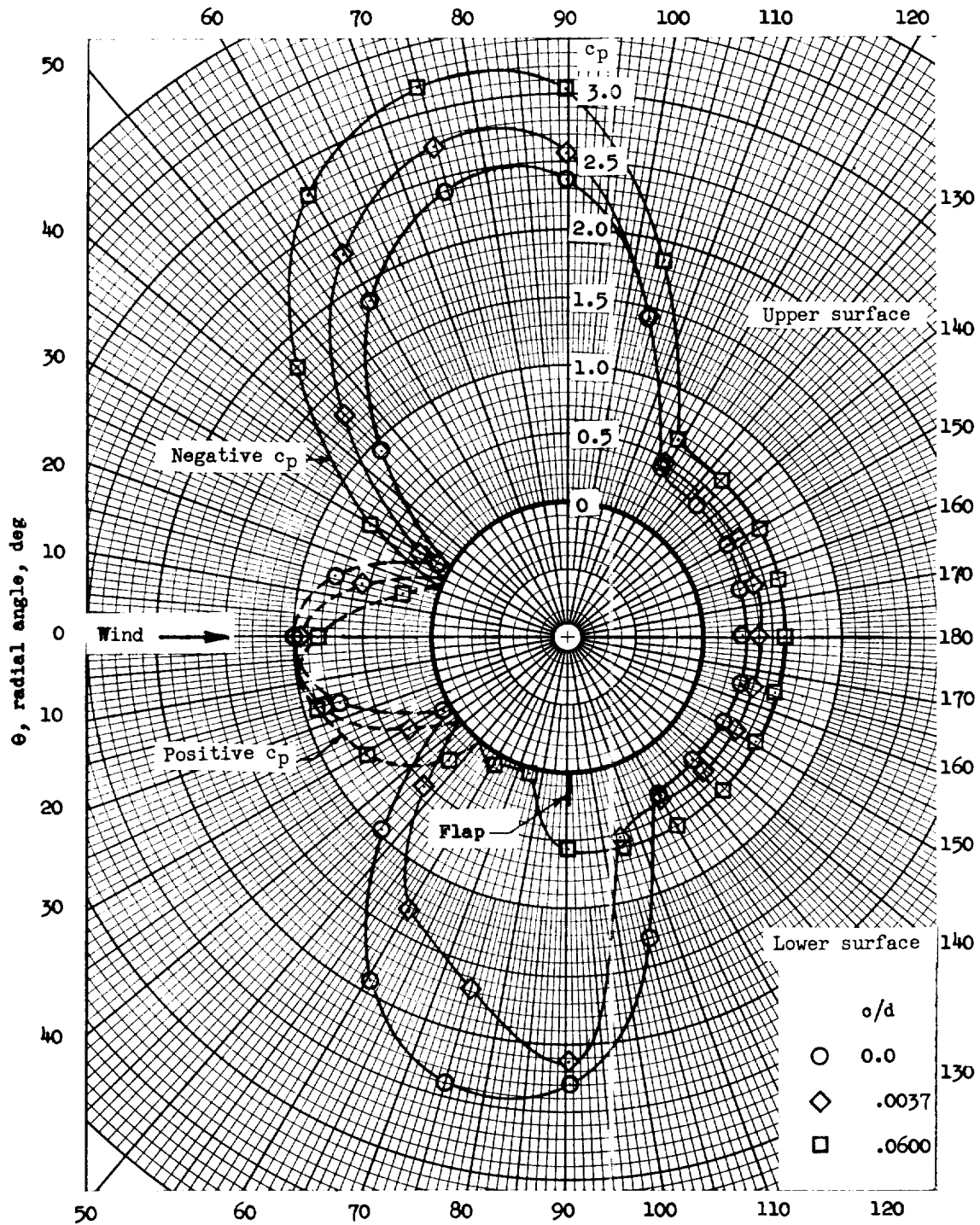


Figure 12.- Effect of flap height on the pressure distribution about a circular cylinder.  $\delta = 90^\circ$ ;  $R = 520,000$ .



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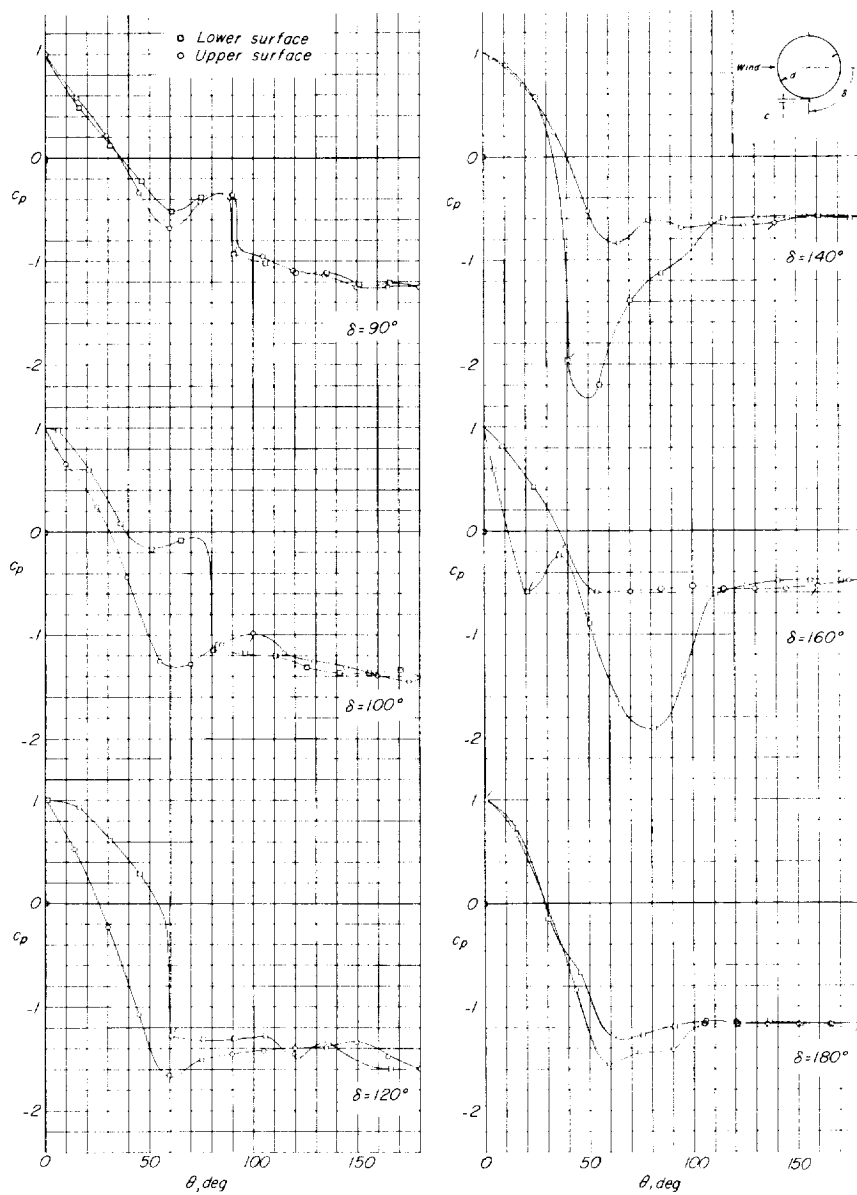
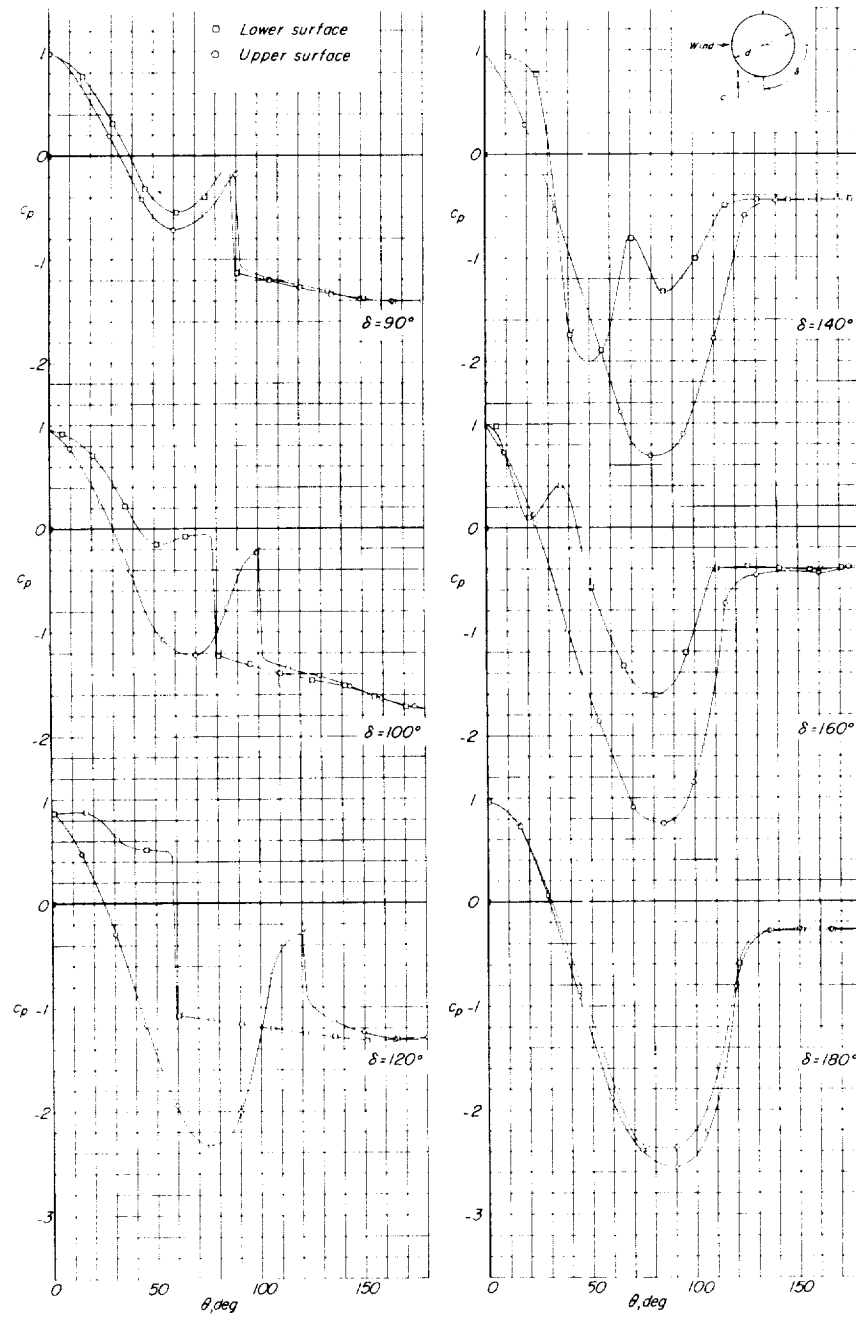
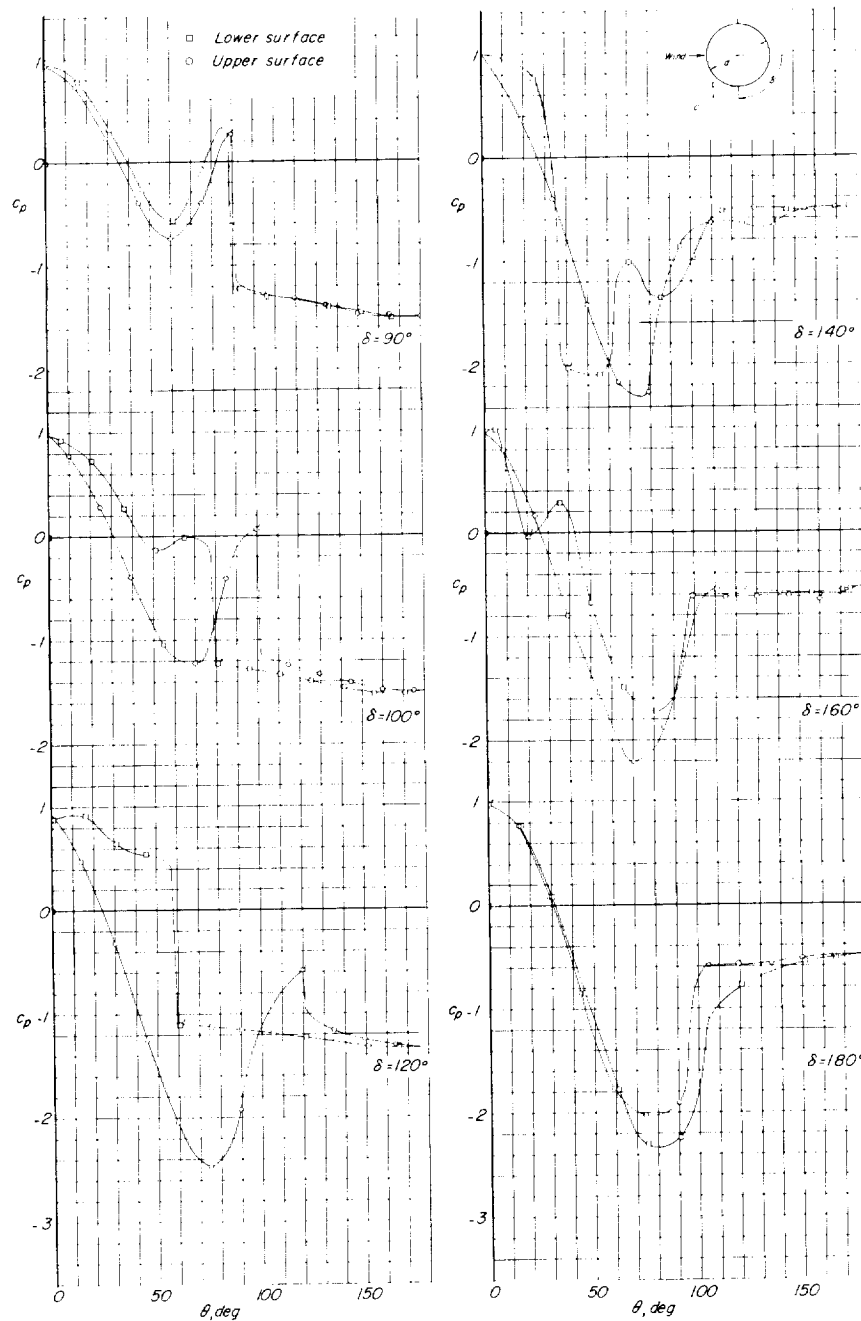
(a)  $R = 190,000$ .

Figure 13.- Effect of flap angular position on the pressure distribution about a cylinder having two flaps  $180^\circ$  apart. Ticks indicate flap position on respective surfaces.  $c/d = 0.06$ .



(b)  $R = 520,000$ .

Figure 13.- Continued.



(c)  $R = 1,038,000$ .

Figure 13.- Concluded.

